Component technologies of HVM source for reliable, high average power operation

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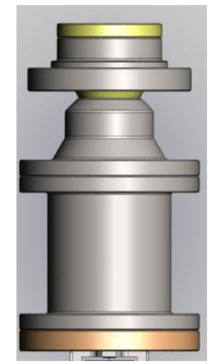
June 6, 2012, Maui Hawaii

Gigaphoton update

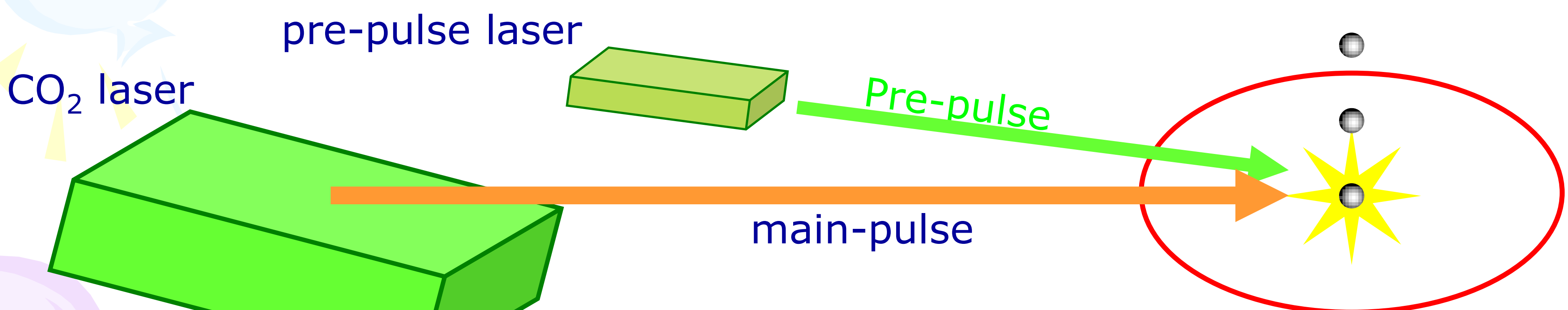
Higher CE challenge more than 5%

3 key challenges

Droplet generator

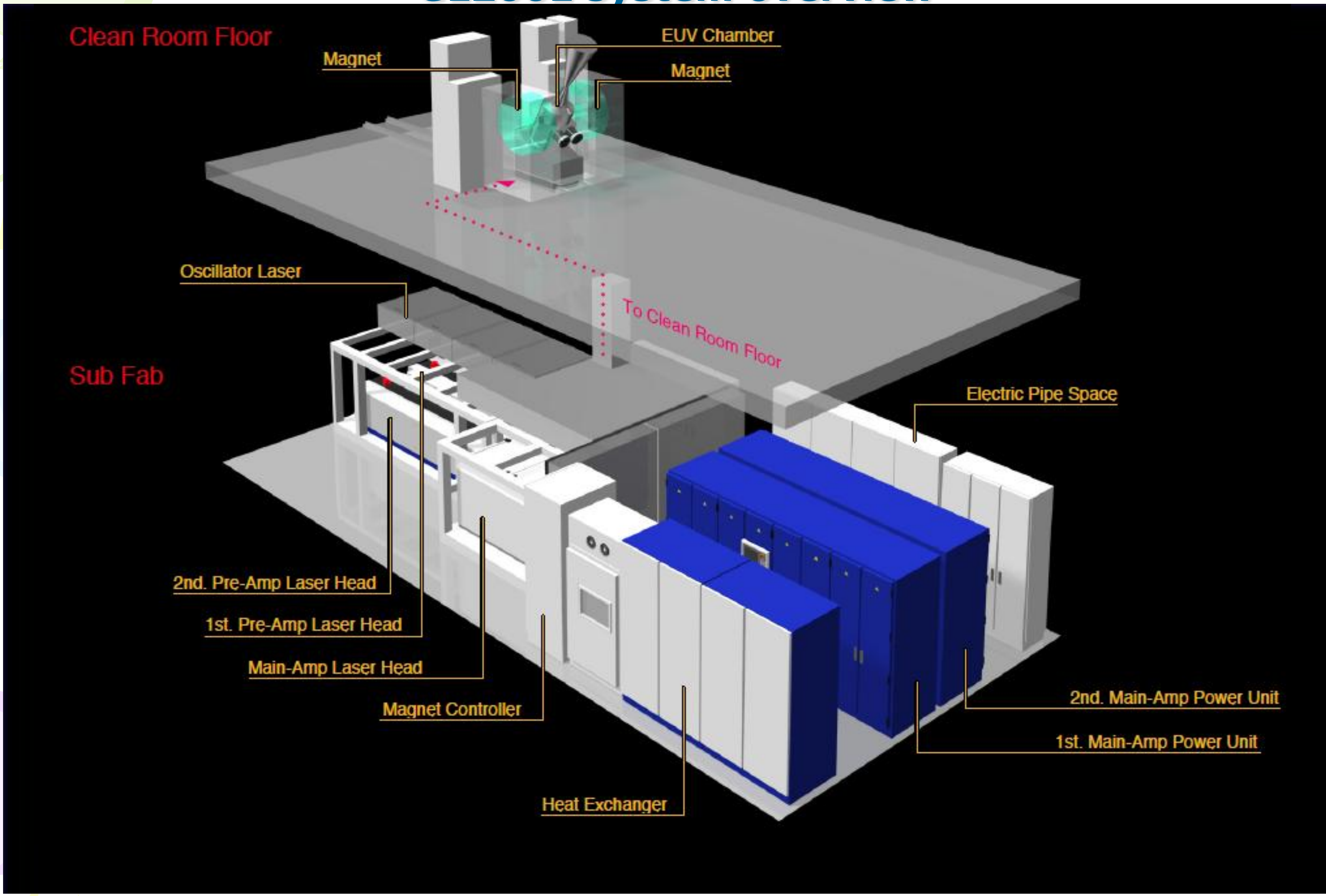


- Small droplet supply with **Droplet on Demand**
- **Dual wavelength Laser Produced Plasma**
- Perfect ionization and **Magnetic mitigation**



- Stable and small droplet
- high power CO_2 laser
- the best plasma creation

GL200E system overview



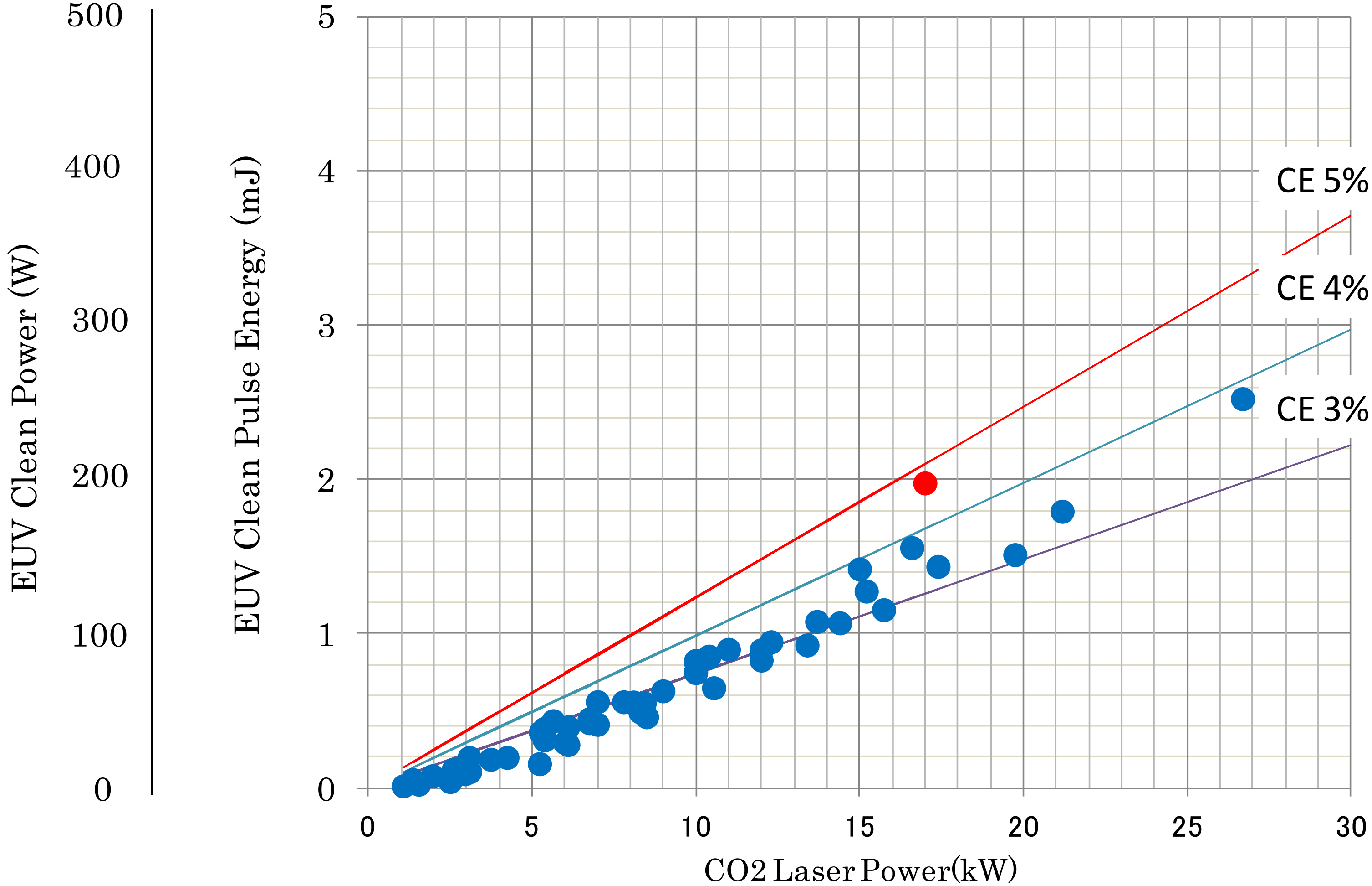
Maximum 7W clean power at Proto system is on line

- EUV light generated at Proto system

Gigaphoton update

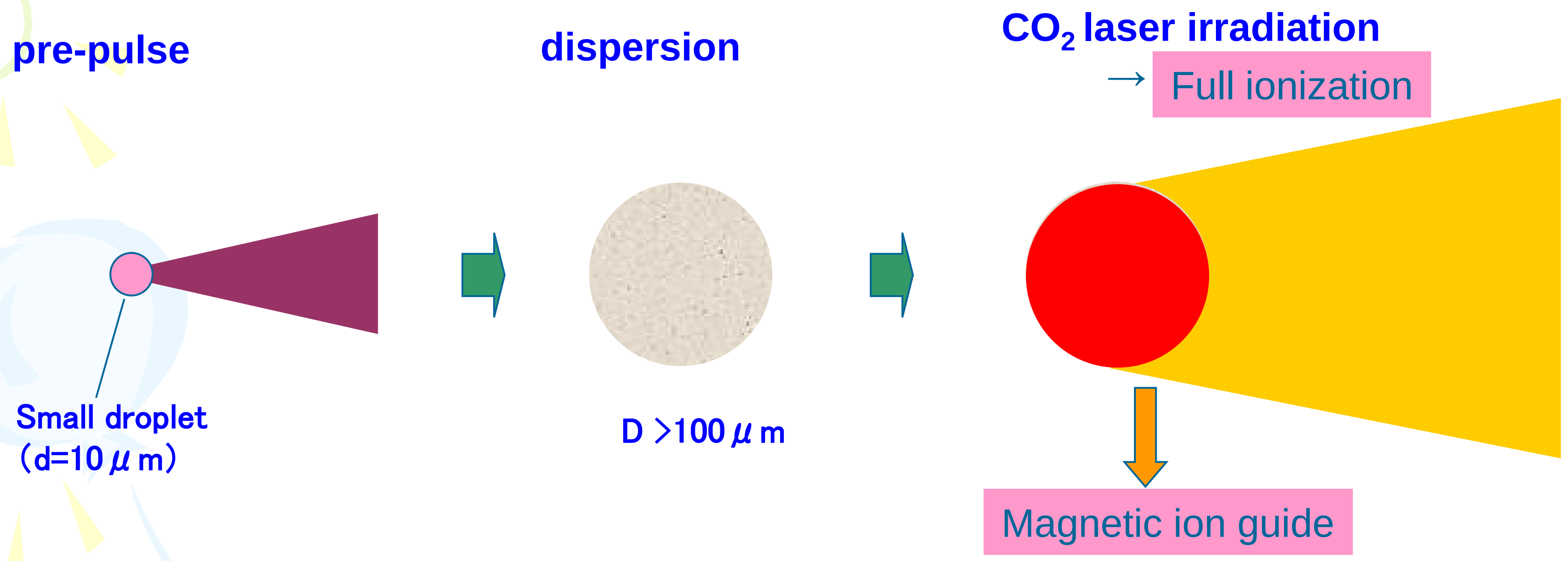
Dual wavelength Laser Produced Plasma

- After CE optimization
  - 3.3% →3.8%→4.7% (@ pilot condition)



New champion data of CE = 4.7% (May.2012)

Basic architecture of LPP EUV source



Double pulse method

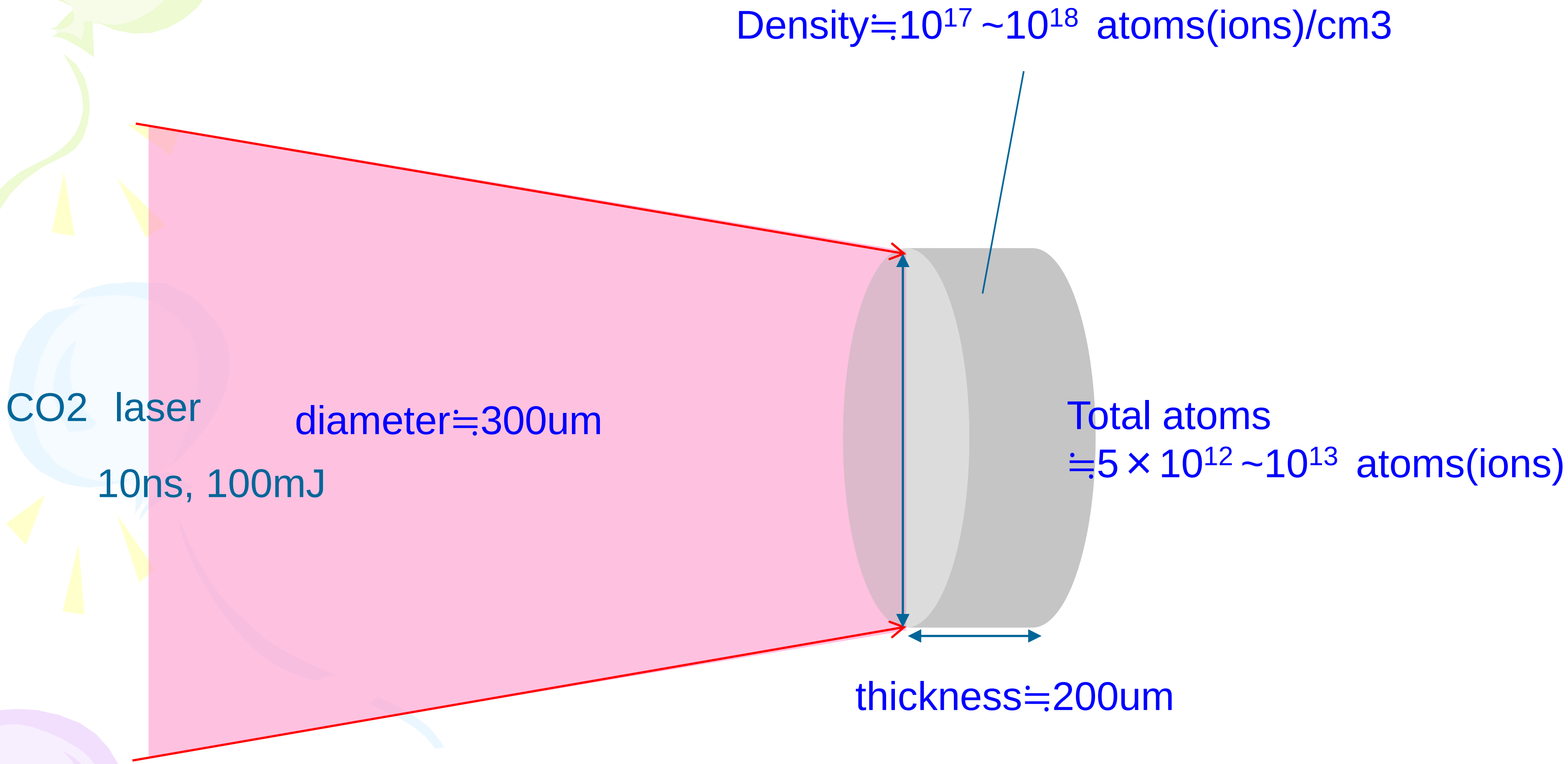
Optimize density, temperature and spatial distribution
for main pulse heating to achieve high EUV conversion efficiency
and **full exhaust of Sn atoms**

Clean EUV source technology

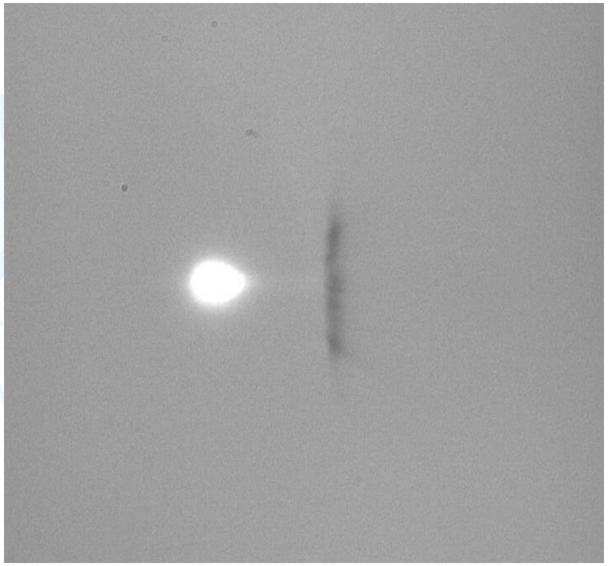
- No fragment generation and deposition
- Metal vapor control

- Pre-pulse optimization for fine cluster generation
- Avoid slow heating of clusters

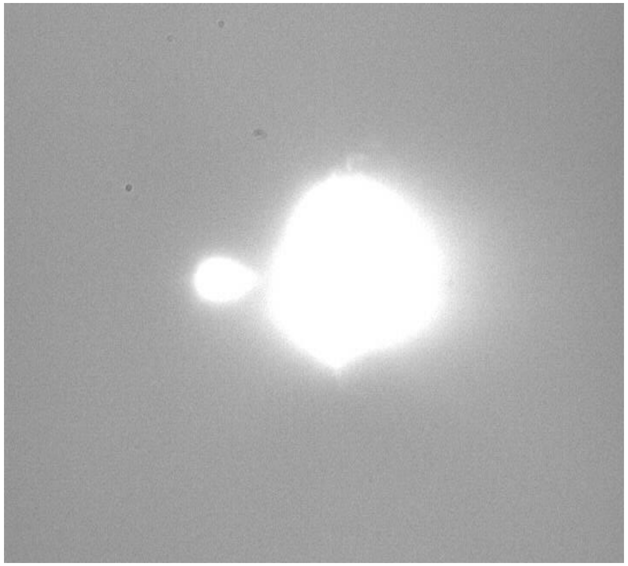
Ideal Sn target



Droplet with pre-pulse irradiation



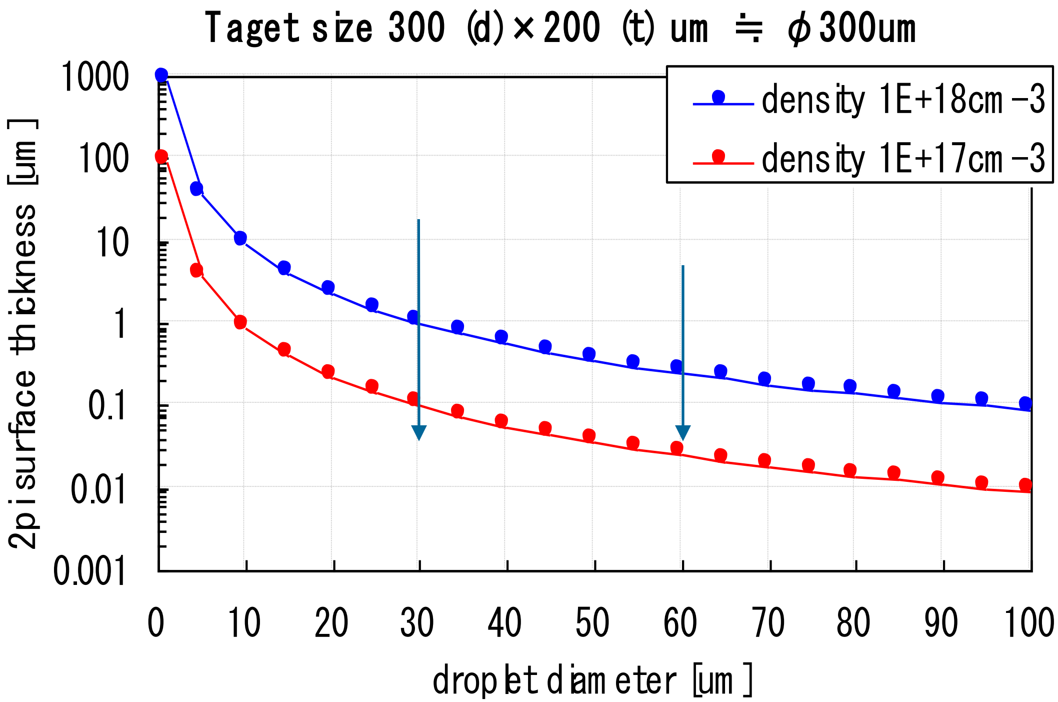
Without main pulse

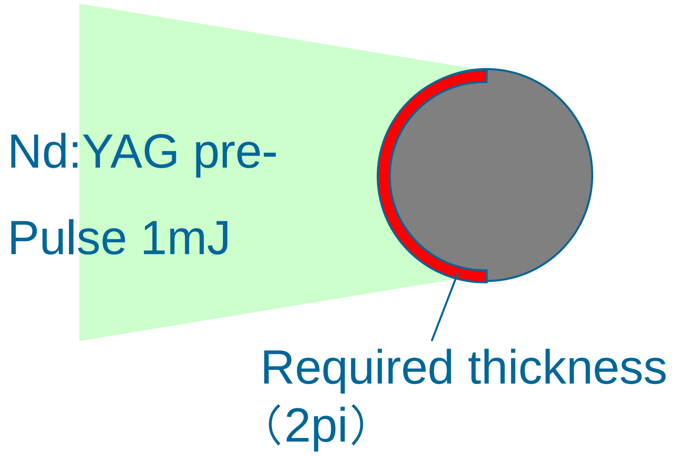


With main pulse

Data by Gigaphoton Inc

Required atoms and droplet surface（2pi）atoms





30um droplet : 0.1～1um（density 10^{17}～10^{18}）

60um droplet : 0.025～0.25um（desnity 10^{17}～10^{18}）

Number of included atoms

Droplet Dia. (um)	Sn	Xe
10	1.9×10^{13}	7.0×10^{12}
20	1.6×10^{14}	5.6×10^{13}
30	5.2×10^{14}	1.9×10^{14}

Atomic weight： Sn 118.7 Xe 131.3

Dynamics of Sn droplet after pre-pulse irradiation

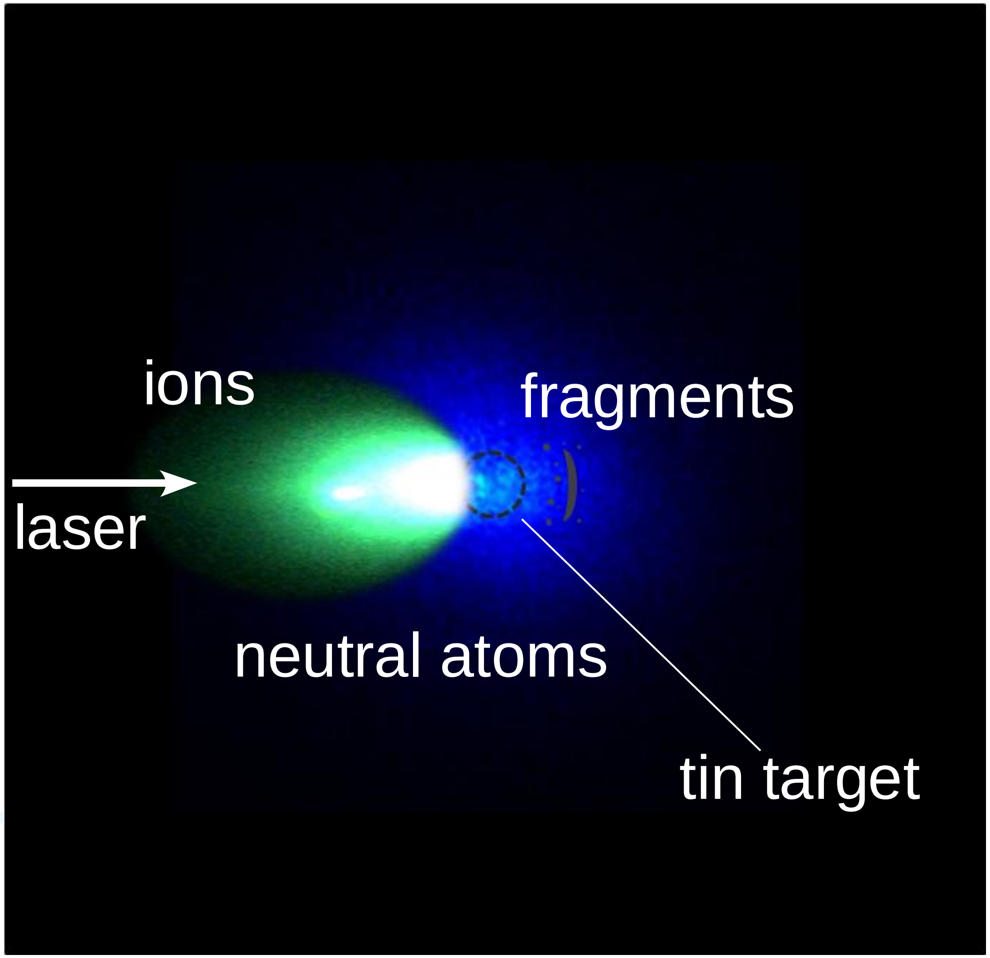
Droplet: spatially and electrically isolated object

Ablation

Spallation

Fragmentation

vaporization



Liquid droplet discomposes into energetic plasma ion and neutrals, and slow gas and fragments (the majority of the target material)

Vaporization (static)

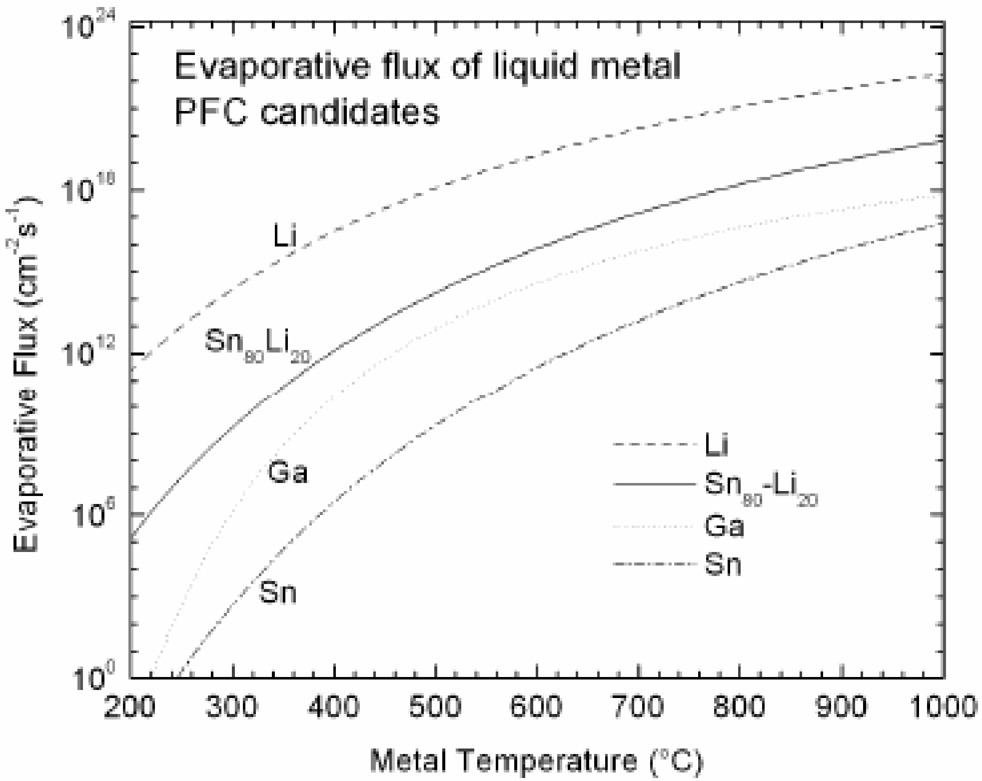


Figure 1. Evaporation flux as a function of surface temperature for four of the primary candidates for liquid metal PFC materials. The curves for Li and $Sn_{80}Li_{20}$ are from [1] while those for Sn and Ga are from [3] and [4], respectively.

10^{-5} atom emission from 20μm droplet during 10cm flight at 60m/s speed

LPP modeling & Warm dense matter

Exact hydrodynamics modeling needs EOS (+ kinetic effects) on whole ablation pathways.

- Binode & spinode: liquid-gas mixture .

(1) Adiabatic expansion with droplets creation after a weak heating.

(2) Adiabatic expansion with partial re-condensation after strong heating.

(3) Adiabatic expansion with a transition into plasma and gas phases.

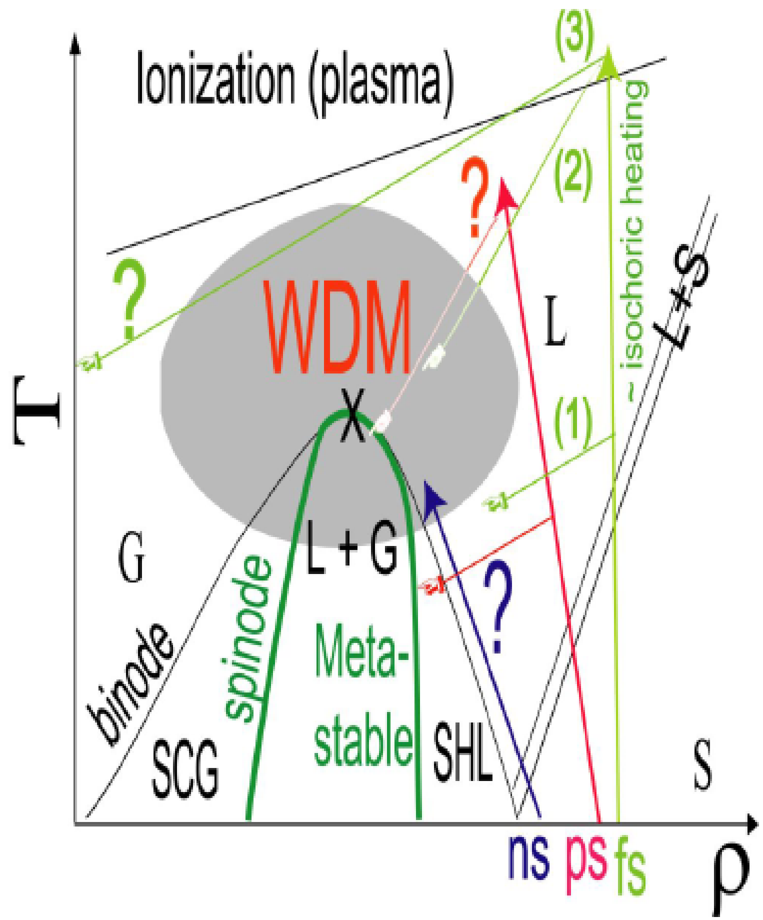
Lescoute, Phys. Plasmas (2008).

Initial stage pass through:

WDM: 0.1 eV ≤ T ≤ 10 eV, 0.01 g/cc ≤ ρ ≤ 10 g/cc

Solid & Liquid Sn: ~ (5-7) g/cc

- Warm + dense → rapid hydrodynamic → transient phenomena.
- Evaporation & condensation kinetics are fast.
- Laser absorption: not well-known.
- Critical parameters: not well-known.



Typical density – temperature space. X: critical point.
SHL: superheated liquid. SCG: supercooled gas.
ns & ps & fs : typical laser pulse in EUV source.

LPP modeling & Warm dense matter

Superheating (supercooling) is demonstrated for solid and liquid.

Iglev, Nature (2006) & Luo, Phys. Rev. B (2003) & Xu, J. Heat Trans. (2002) & Lewis , Appl. Surf. Sci. (2009).

Thermodynamic (equilibrium stage)

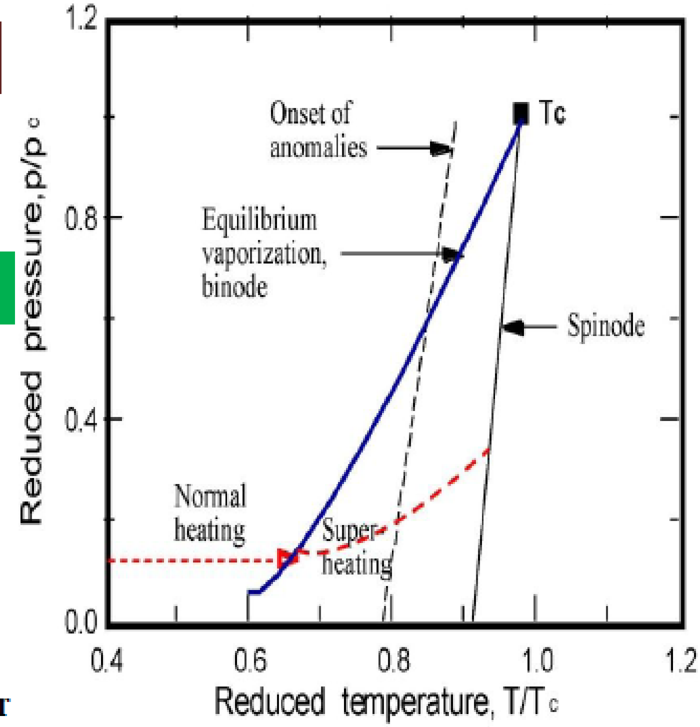
Slow heating → binode → Clausius-Clapeyron equation.

Non-equilibrium (metastable liquid)

High energy deposition → metastable state → phase explosion, spallation, fragmentation

- Pure liquid: homogenous nucleation time ≈ ns.
- Liquid metals: spontaneous nucleation is longer or not realized even for very large superheating (is under investigation by molecular dynamics).

Bulgakova, Appl. Surf. Sci. (2007), etc.



Typical P-T diagram of phase explosion. Dome in solid line is binode. Dome in dashed line is spinode. Tc and pc are critical parameters.

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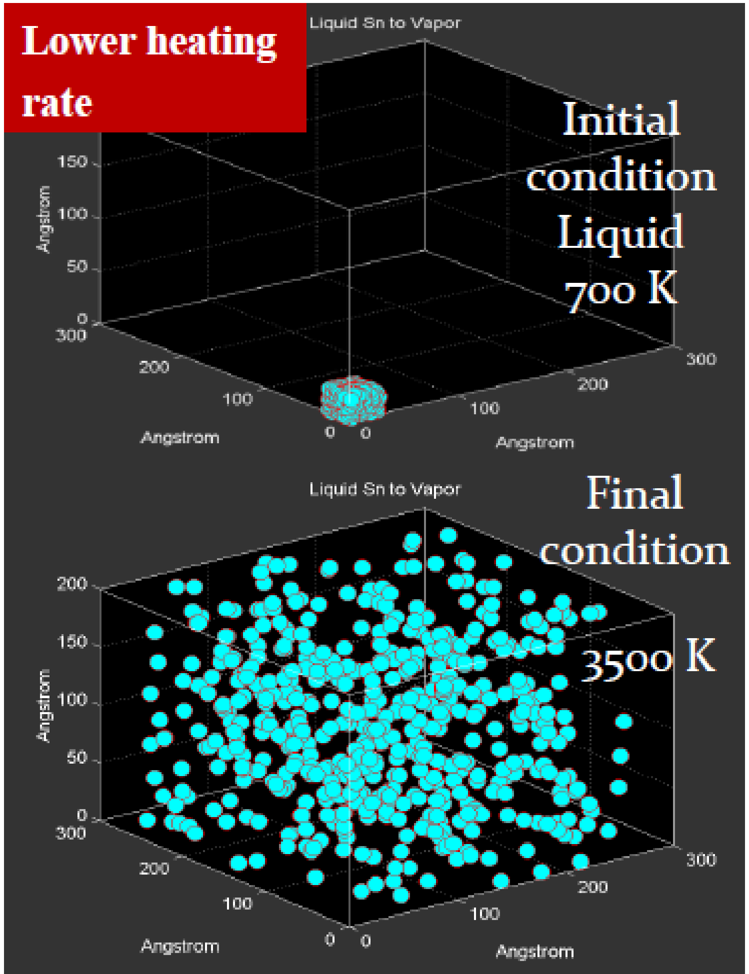
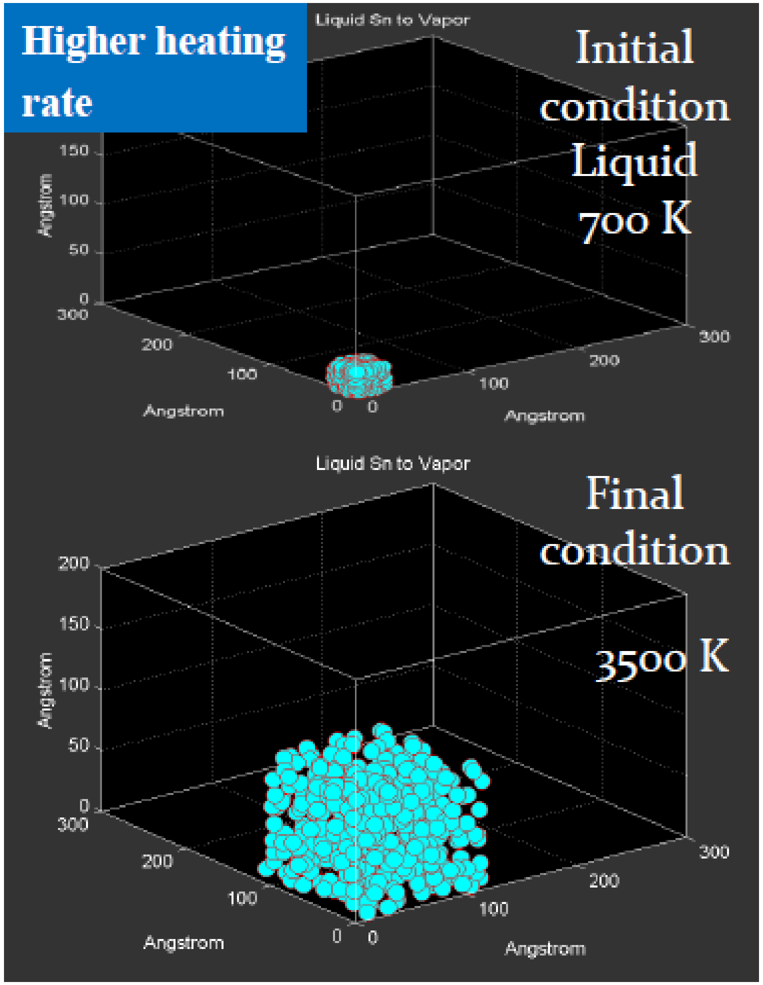
Molecular dynamics simulation

Boiling & Vaporization

Inertial confinement effect





Thermal history changes the thermodynamic pathways.

Pressure in transient phase

atomic motion + intermolecular force

$$P = \rho k_B T + \frac{1}{3V} \left\langle \sum_{i=1}^{N} \sum_{j<i} \vec{F}_{ij} \cdot \vec{r}_{ij} \right\rangle$$

$$T = \frac{m}{3 N k_B} \sum_{i=1}^{N} \left(\sum_{\alpha=1}^{3} \left(v_{i,\alpha} - \bar{v}_{\alpha} \right)^2 \right)$$

P(fast heating) > P(slow heating)

JOURNAL OF APPLIED PHYSICS **109**, 123306 (2011)

Simulation of particle velocity in a laser-produced tin plasma extreme ultraviolet source

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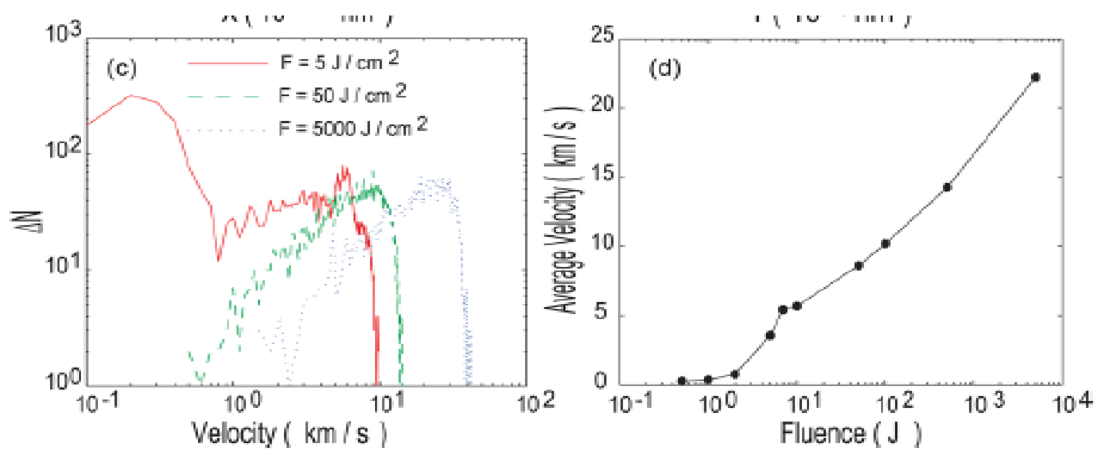


FIG. 6. (Color online) (a) The initial condition is assumed to be a small Sn sample size of $\simeq 2\times 2\times 35$ nm. A laser pulse is irradiated from the top surface of the sample. (b) A typical snapshot of particle velocities perpendicular to the laser direction and charge states against the norm of the position vector r before the maximum intensity of a laser pulse with a fluence of 500 J cm^{-2}. (c) The velocity distribution of Sn particles at various fluences of 5, 50, and 5000 J cm^{-2}. (d) The weighted average velocity values versus the laser fluence.

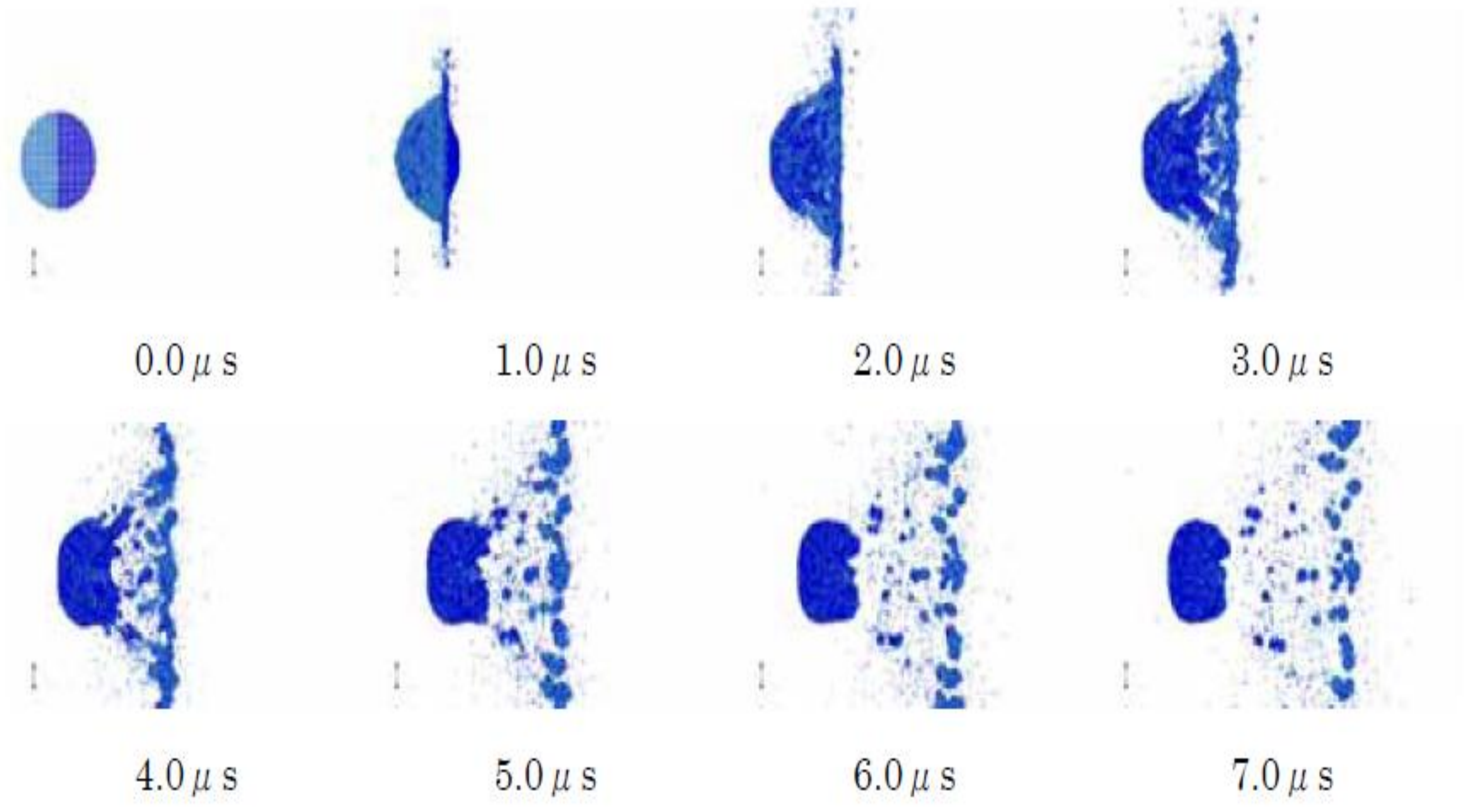
Fluid mechanical simulation of doplet fragmentation

Moving particle semi-implicit method : MPS

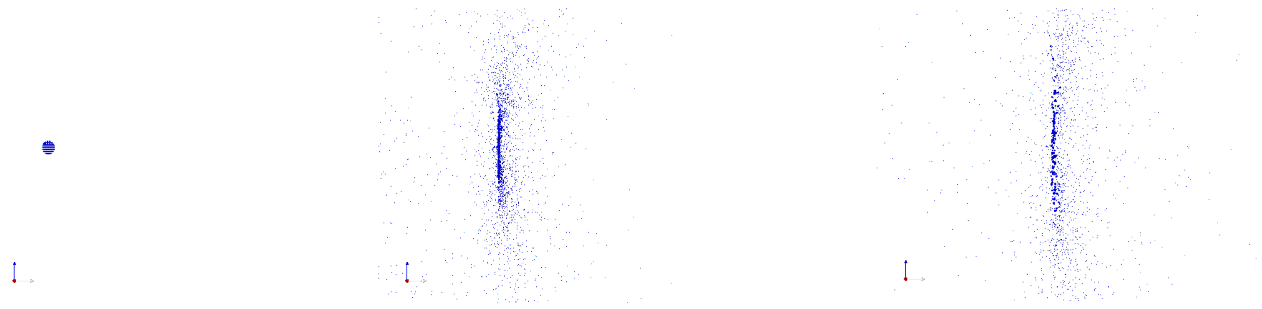
100µm Sn droplet with prepulse irradiation

side top

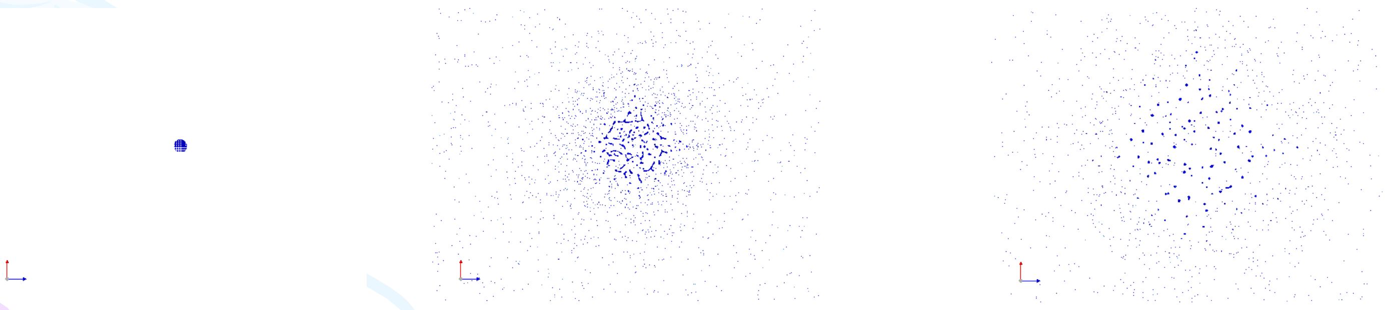
Laser prepulse gives 100µm droplet 15m/s horizontal speed and partial fragmentation



Optimized condition : 10μm droplet with 300m/s speed by prepulse



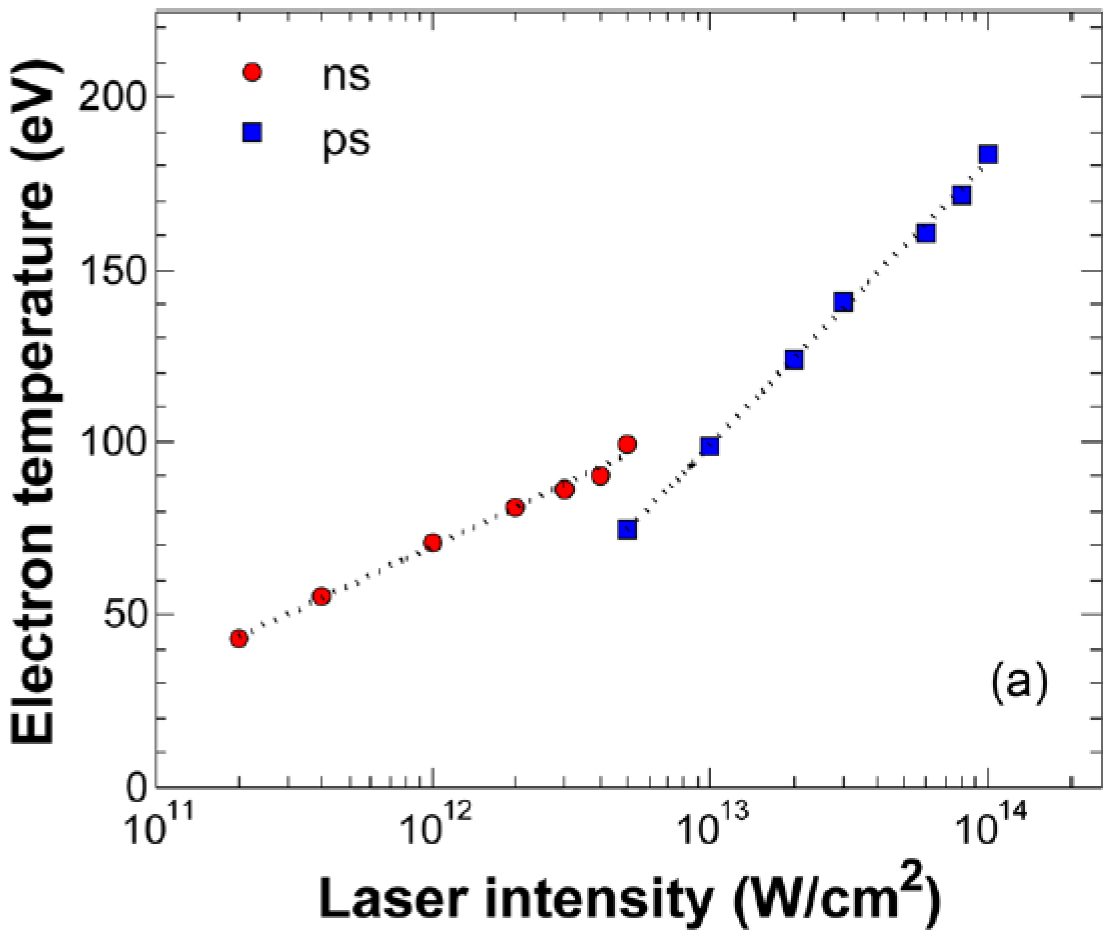
Oblique image



On axis image

Mist generation is realized with 10μm Sn droplet

Plasma temperature vs laser pulse width



Te(ns laser plasma) < Te(ps laser plasma)

Ion speed vs laser pulse wisth

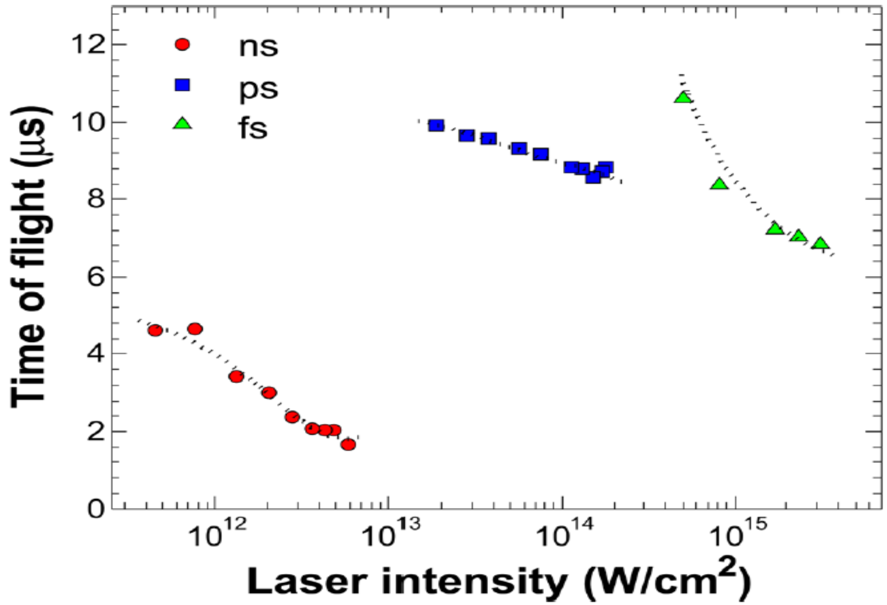
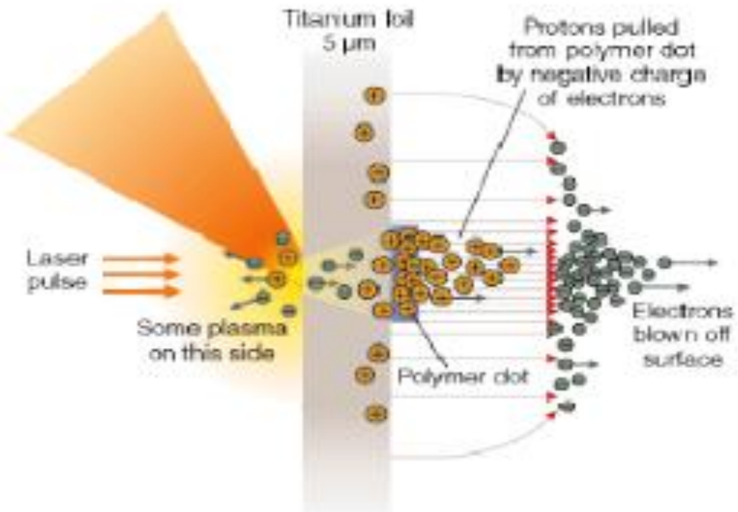


FIG. 4. (Color online) Ion TOF signals observed for plasmas produced with ns and ps Nd:YAG lasers, and the fs Ti:Sapphire laser as a function of laser intensity.

V_{ion}(ns laser plasma) > V_{ion}(ps laser plasma)

From T.Cummins et.al. Appl.Phys.Lett. **100,** 061118 (2012)

Mechanism of fast ions ; ambipolar diffusion



Example from TNSA (target normal sheath acceleration)

V_{ion} is larger for longer time irradiation

Pressure dynamics from MD calculation

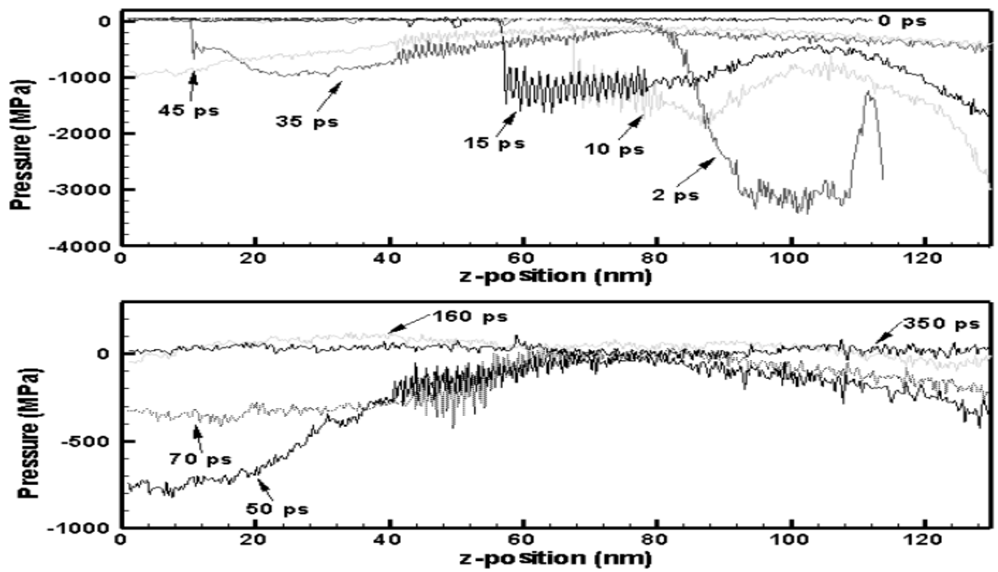
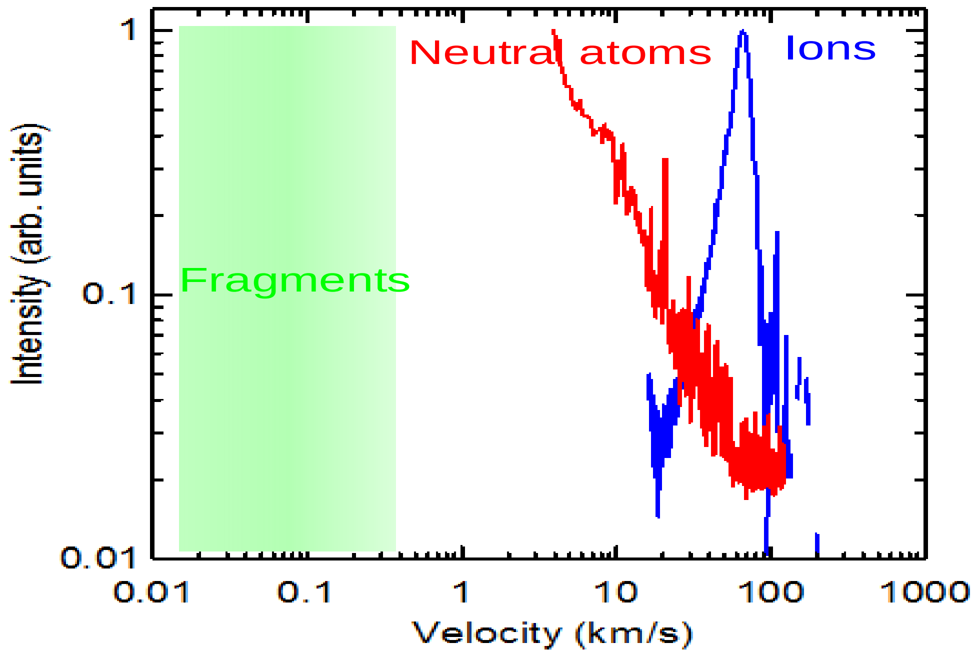


Fig. 4. Pressure distributions at different time steps as a function of position; F_{abs} = 36.5 J/m^2, α = [5 nm]$^{-1}$.

Strong impulse continues less than 10ps due to plasma shield

From H.Y.Lai , J.Chinese Soc.Mech.Eng. **28**, pp577-583 (2007)

Measured Speed ; ions, neutrals and fragments
100μm diameter Sn droplet, 10ns laser



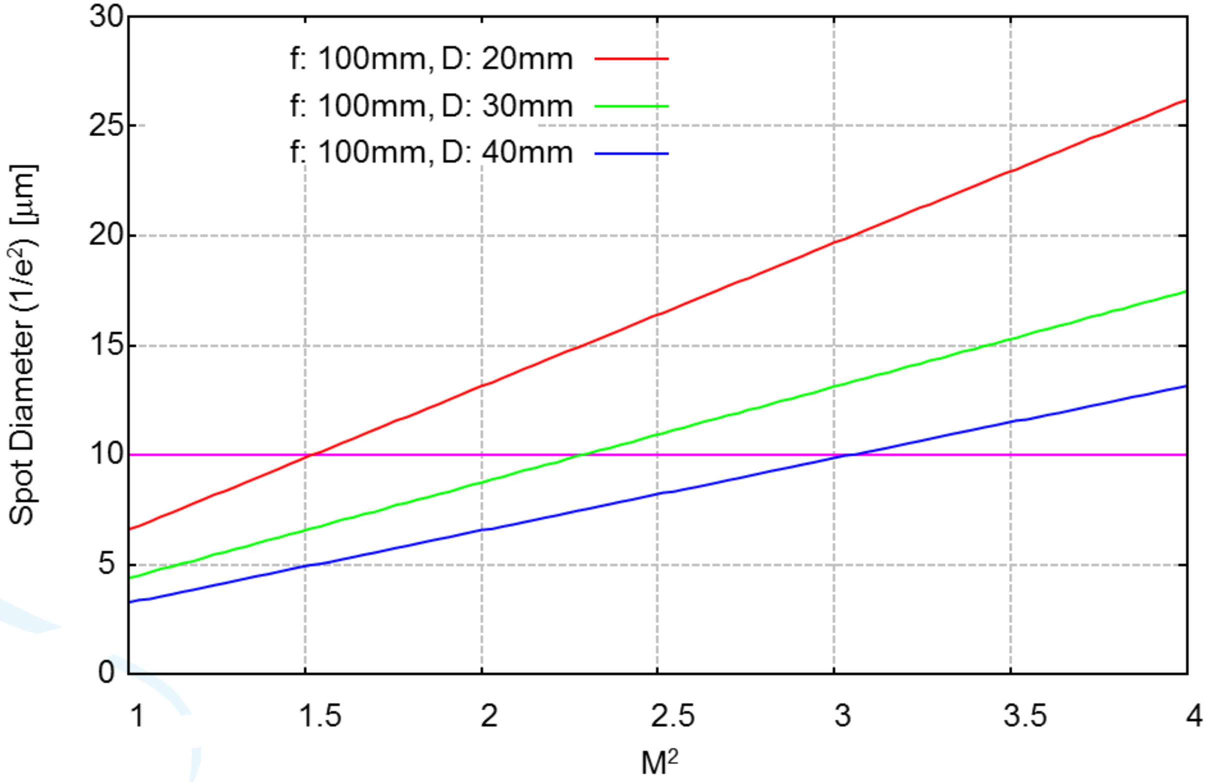
Pre-pulse laser is effective in ps pulse width as impulse for droplet spallation

Conclusion on droplet spallation

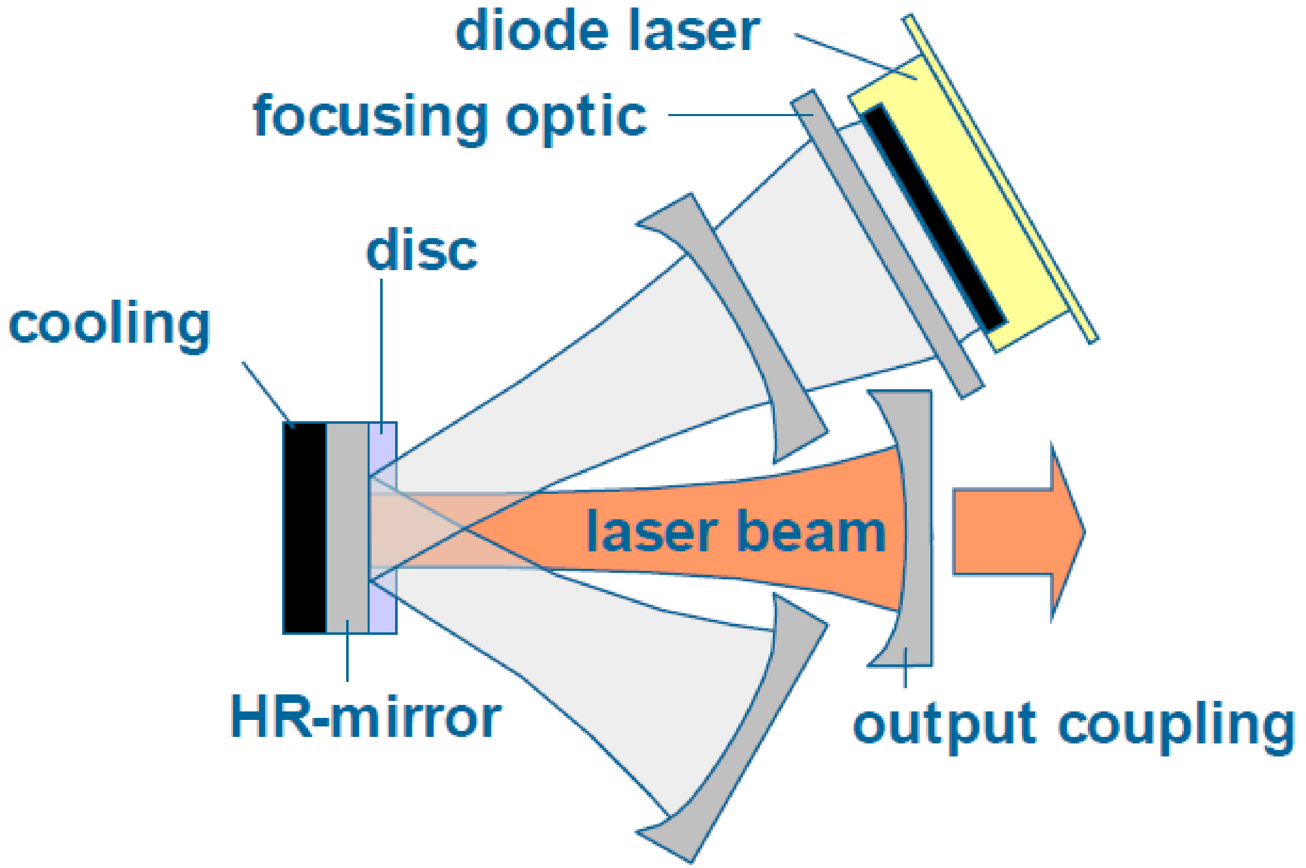
- Pre-pulse Tin droplet dispersion is well characterized
- Ideal Tin target conditioning is realized by 10μm diameter Tin droplet
- Pre-pulse works in ps time as impulse for droplet spallation

- Compact solid state laser for a pre-pulse laser with ps pulse width High beam quality for 10μm spot size focusing

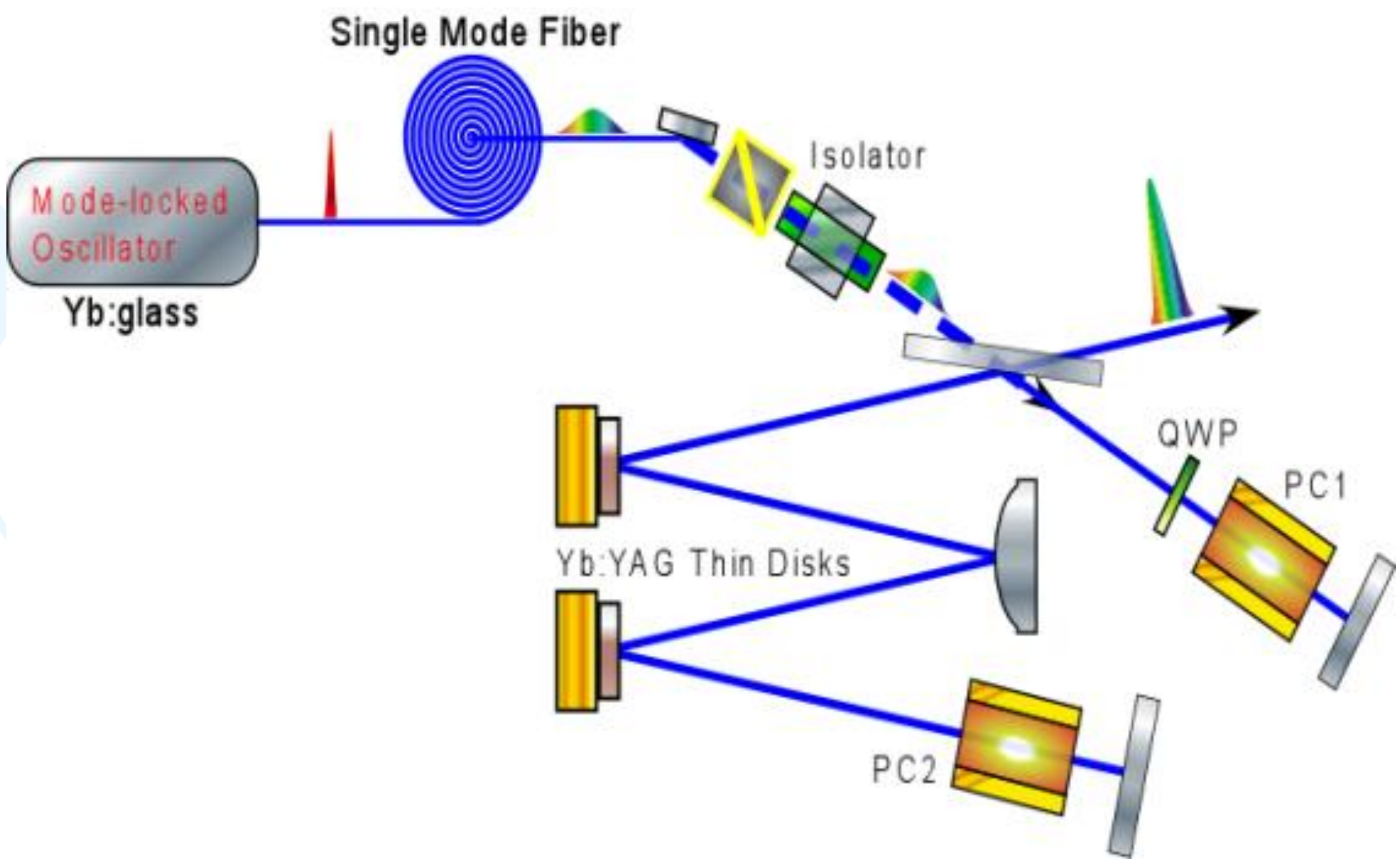
M2 vs spot diameter



Thin disc laser configuration

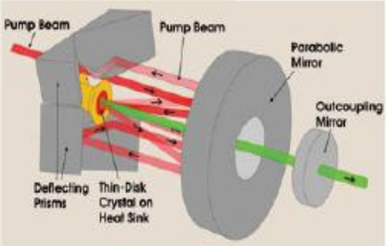


Thin disc laser regenerative amplifier

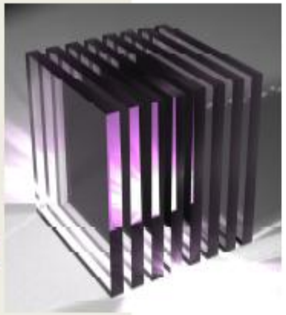


Project Activities of the HiLASE

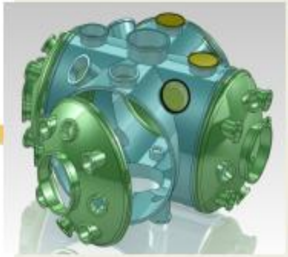
- HiLASE Research Program 1 (Thin disk laser)
  - Development of multi-J, kW class thin-disk laser system
  - Mainly focused on medial and industrial applications
  - Three beam lines with different beam parameters



- HiLASE Research Program 2 (Multi slab laser)
  - Development of 100 J / 10 Hz cryogenically cooled multi-slab DPSSL system scalable to kJ level
  - Applications: Laser-induced damage threshold test (LIDT), Laser peening, Pumping source of OPCPA in the ELI project



- HiLASE Research Program 3 (Applications)
  - Using RA1 and RA2 lasers for industrial applications
  - Applications:
    - EUV(13.5 nm) and Beyond-EUV(6.x nm) light source based on laser-induced plasma,
    - Short pulse X-ray sources based on laser-Compton scattering for biomedical imaging
    - LIDT and Laser peening



Beam Lines of RP1

hilase

Beam Line-A

Oscillator → Pulse stretcher → Regenerative amplifier → Booster amplifier → Pulse compressor → 1 J, 1-2 ps, 1 kHz

Sub-contract

Beam Line-B

Oscillator → Pulse stretcher → Regenerative amplifier → Ring amplifier → Pulse compressor → 0.5 J, 1-2 ps, 1 kHz

500W, High energy

Beam Line-C

Oscillator → Pulse stretcher → Regenerative amplifier → Pulse compressor → 5 mJ, 1-2ps, 100 kHz

500W, High rep. rate

In-house development

Priority issues of beam line B & C
- High beam quality
- High reliability
- Small footprint
- Cost effective

evropský sociální fond v ČR

EVROPSKÁ UNIE

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OP Vzdělávání pro konkurenceschopnost

INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

hilase

HiLASE (High-average power pulsed lasers) is a European R&D project aimed at development of novel type of diode-pumped solid-state lasers (DPSSL) intended for industrial and scientific applications. Within the project "Strengthening capacity of research teams in the field of physical sciences" realized by the Institute of Physics AS CR, v.v.i. we are seeking a candidate for the position of:

Postdoctoral Fellow

"Development of compact, laser-driven source for next generation of EUV lithography"

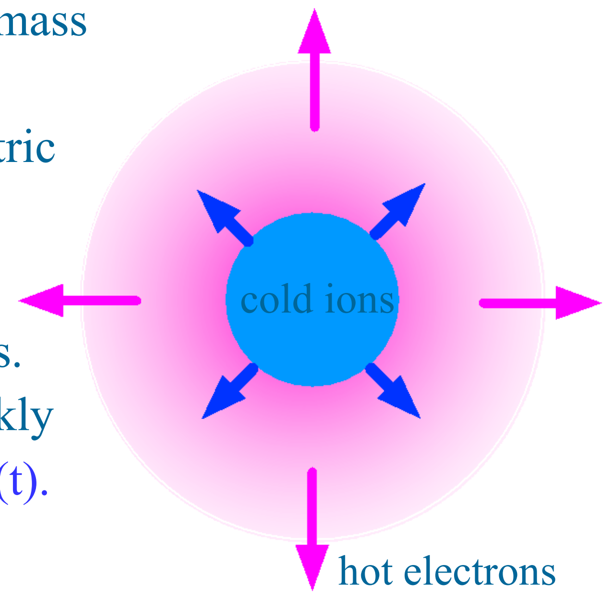
Postdoctoral Fellow

"Development of coherent EUV source for nanotechnology"

Main pulse irradiation

Plasma expansion is characterized by two phases

At $t = 0$ the electron component of a finite plasma mass is heated to a uniform temperature $T_e(r, 0) = T_{e0}$. Hot electrons expand and create an ambipolar electric field $E(r, t)$, which drags the cold ions.



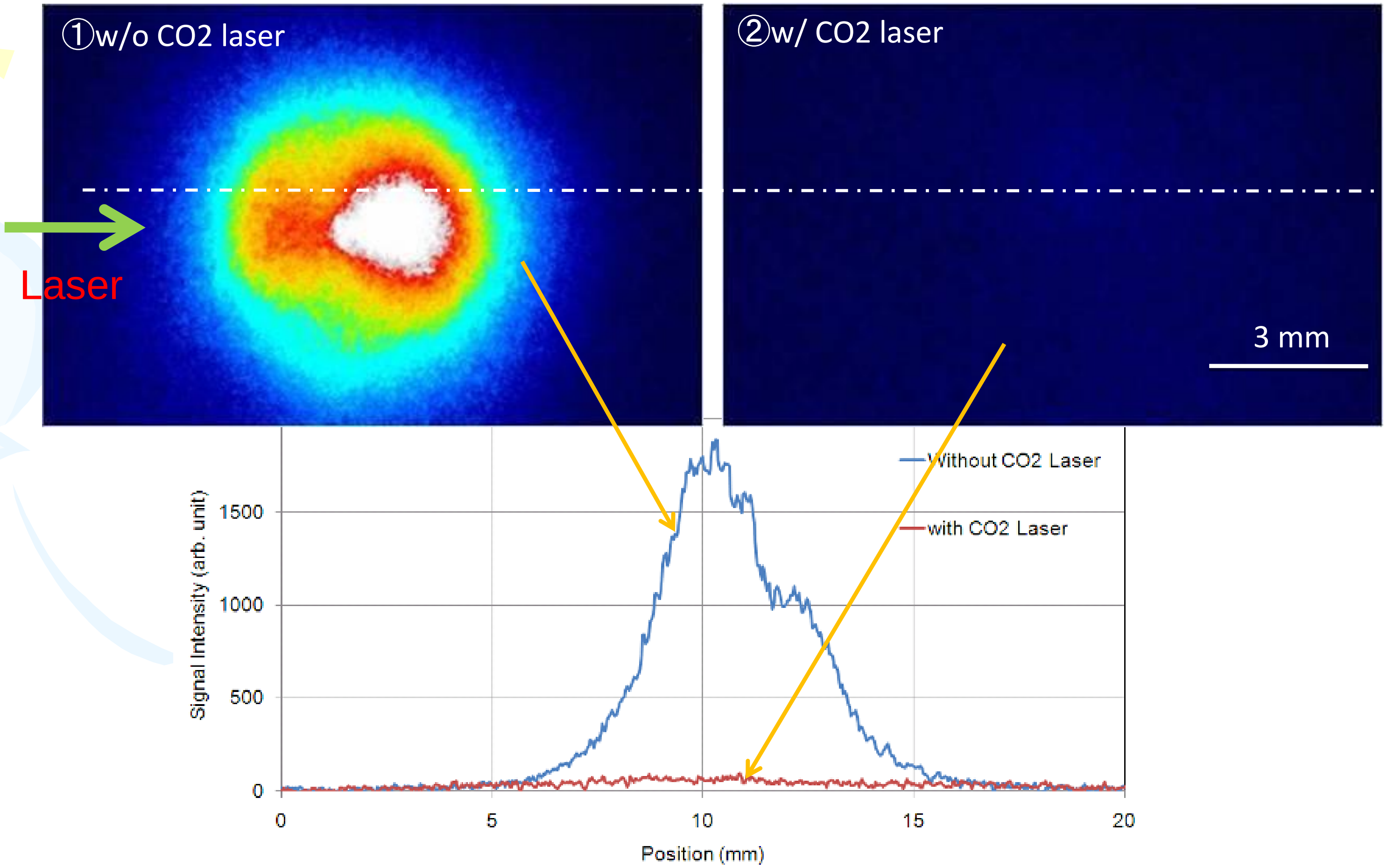
Assumptions

- There are no collisions between electrons and ions.
- At all times, the electron temperature is very quickly leveled off across the plasma volume: $T_e(r, t) = T_e(t)$.

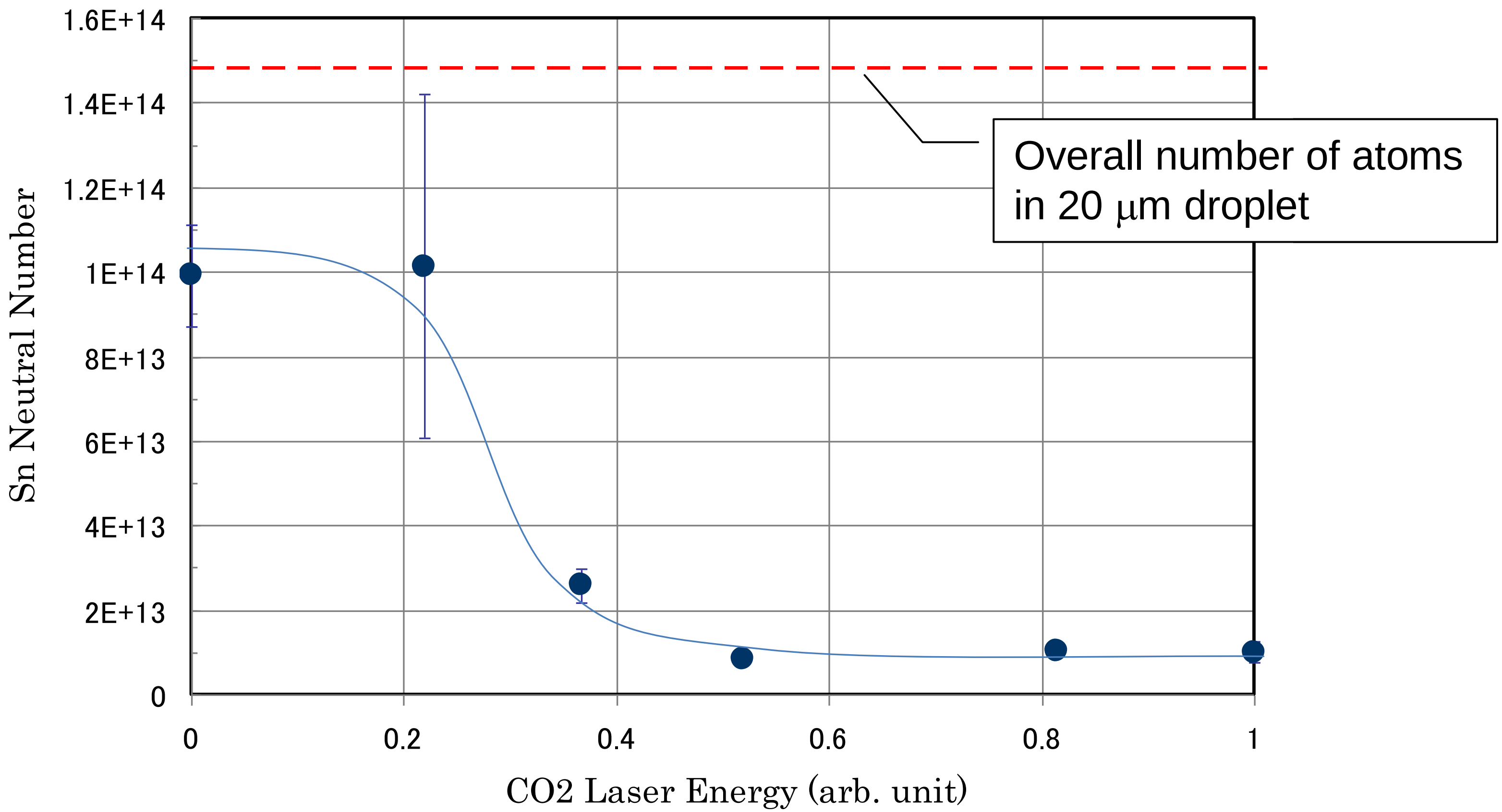
Isothermal phase : during laser irradiation, Energy spectrum is established

Adiabatic phase : after laser irradiation, Energy spectrum is unchanged

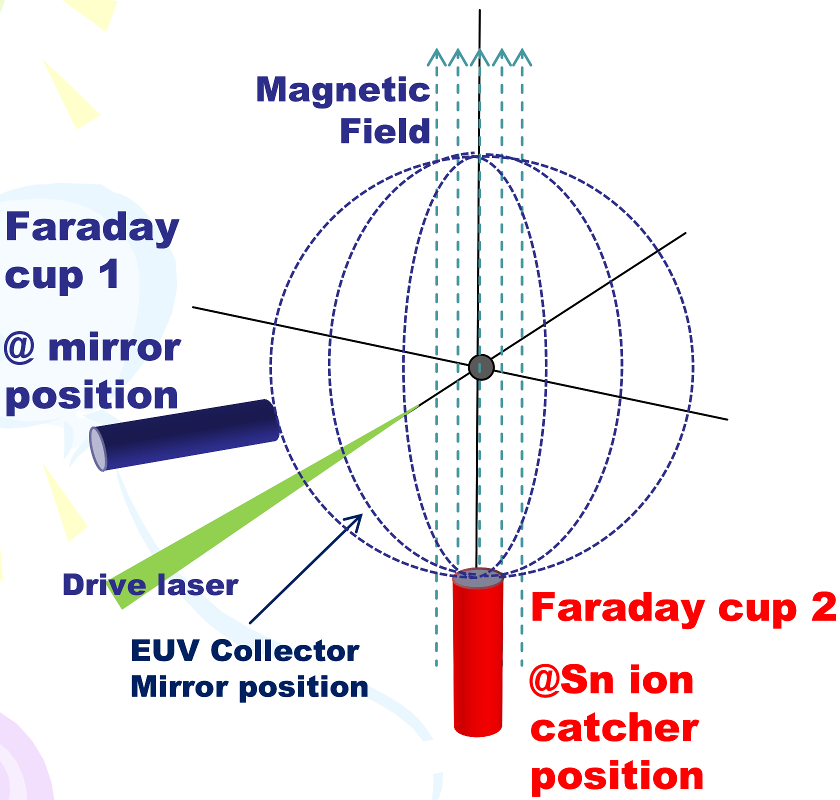
LIF measurements of neutrals in mist target

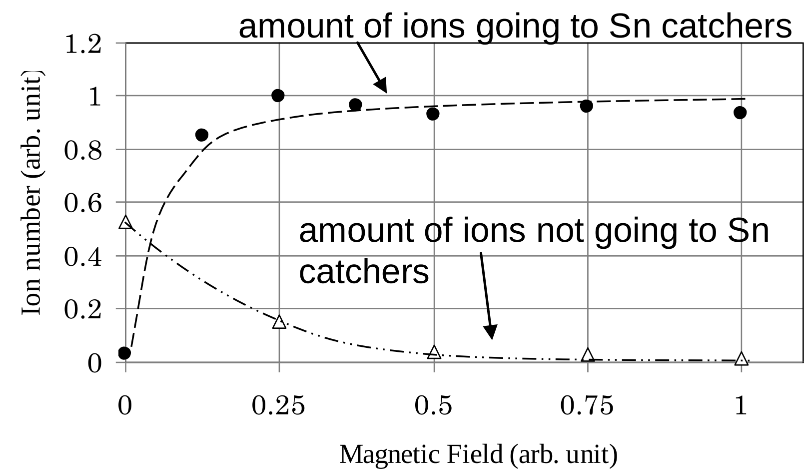


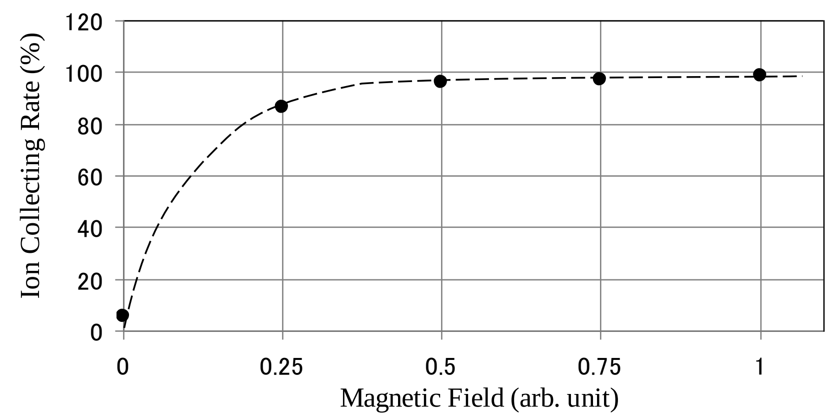
Remaining neutrals



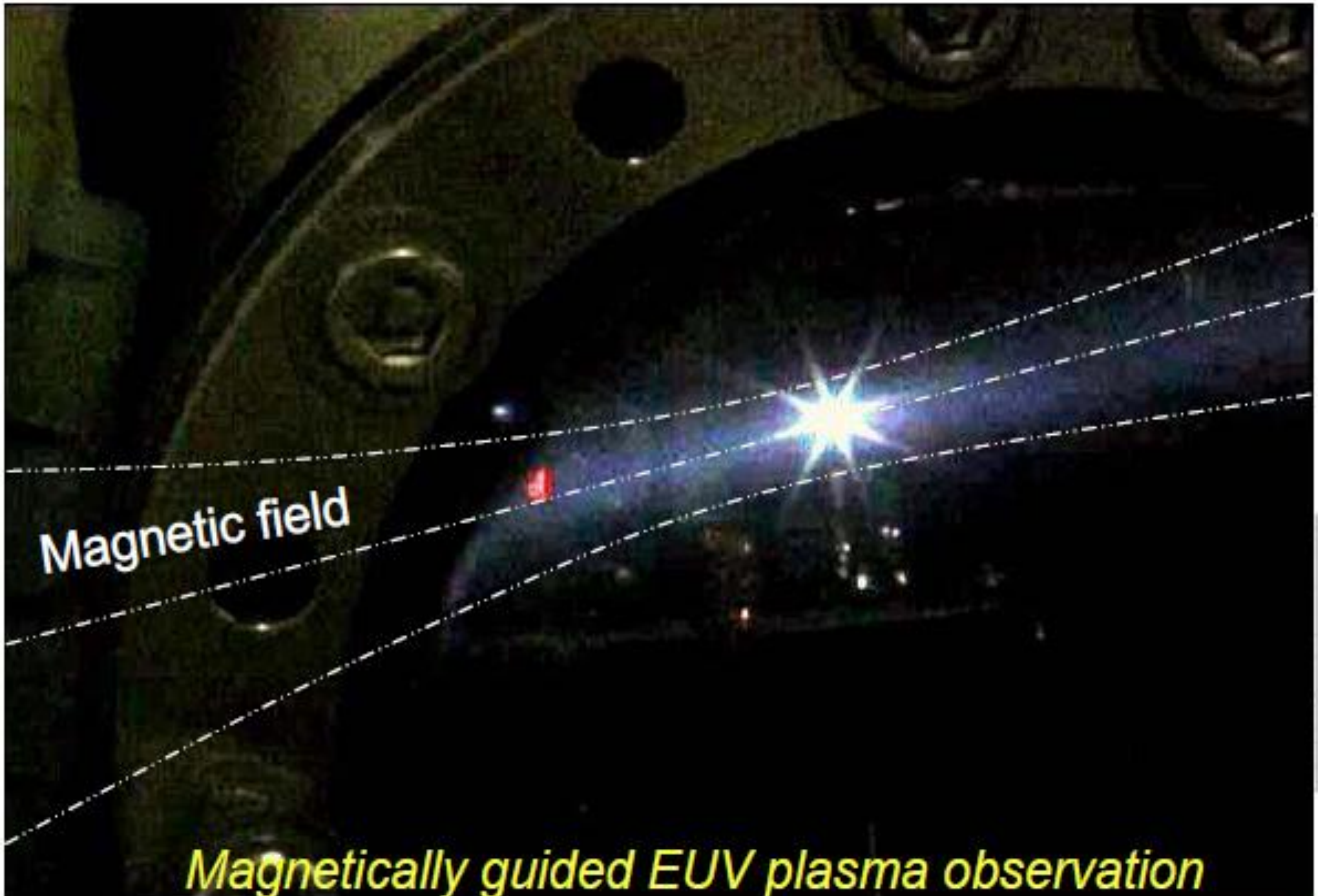
Ion and neutral particle drift in transport magnetic field







Plasma flow from pre-pulsed droplet



Ion flux characterization

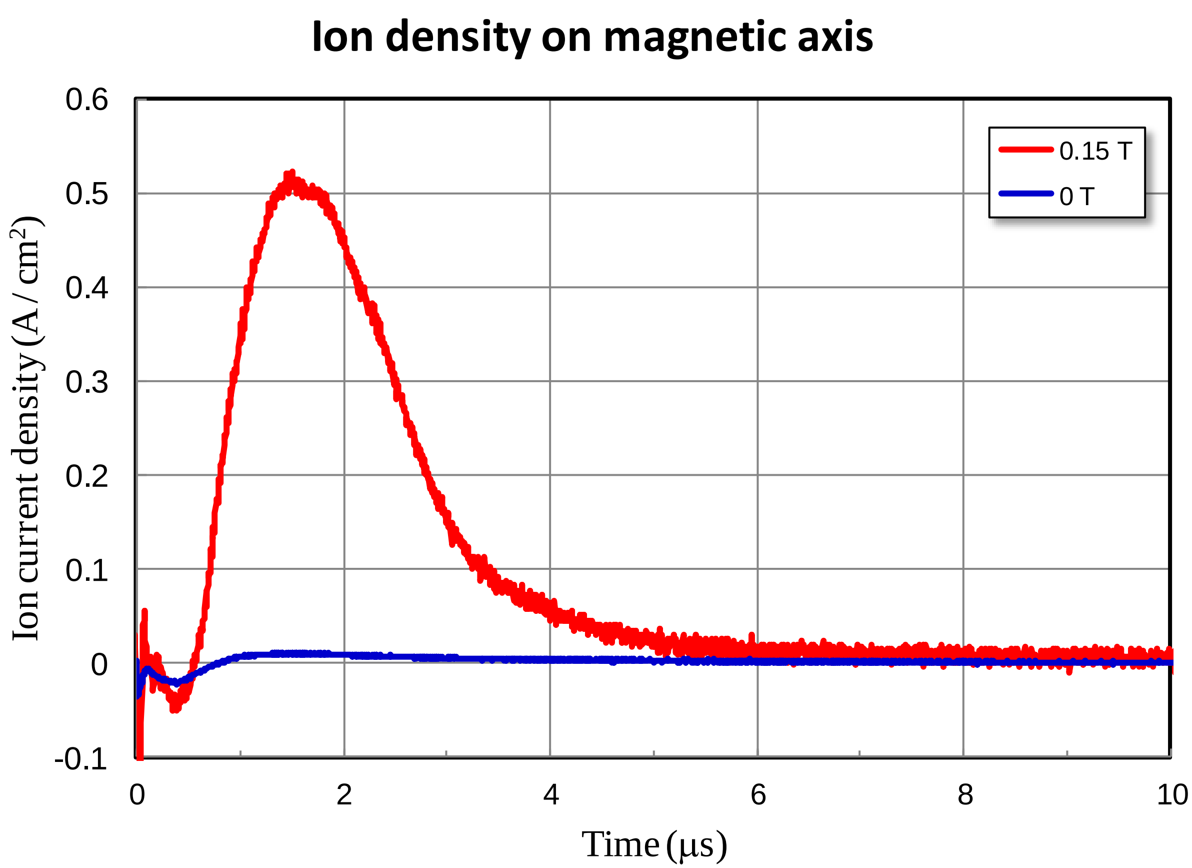
- Droplet
  diameter 20 um

- Laser
  CO_2 pulse energy   166 mJ
  Pulse width 20 ns(FWHM)
  Spot size 300um(1/e^2)
  With pre-pulse laser

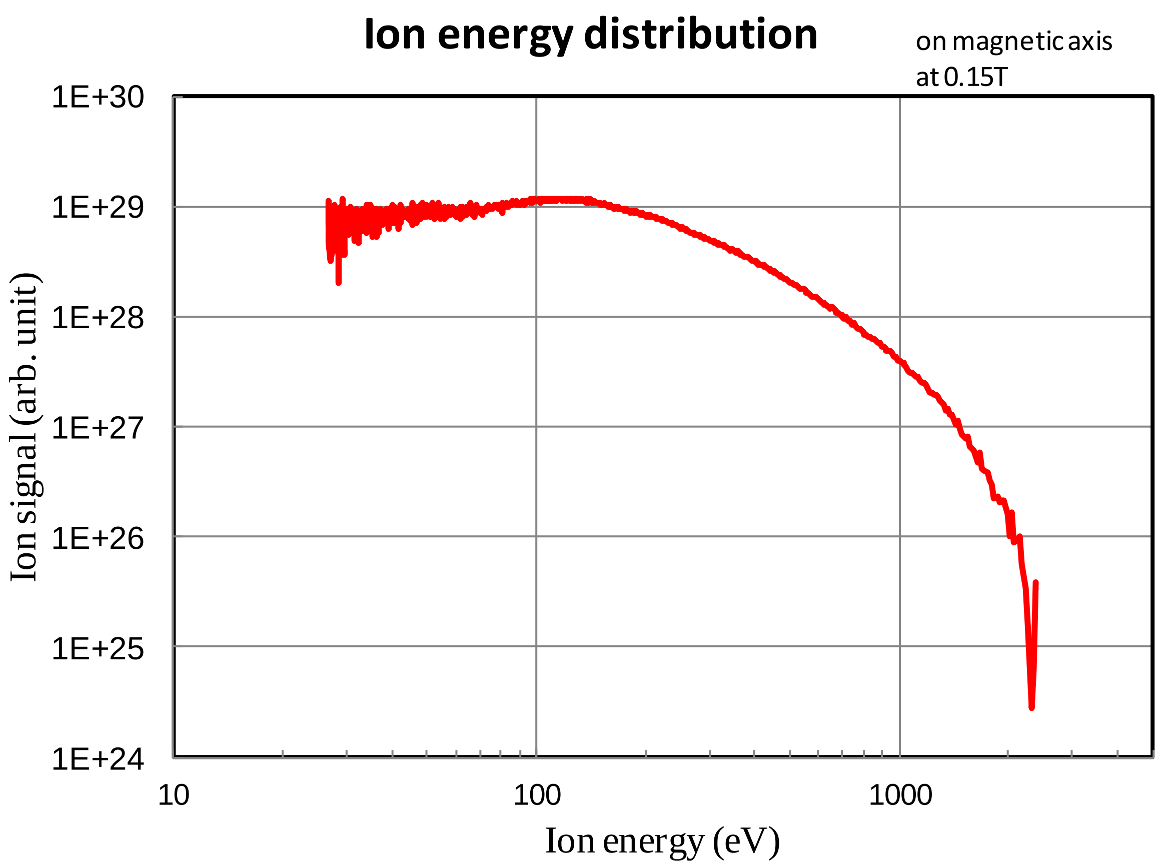
Magnetic field
  0.15 T at center

- Faraday cup
  clear aperture 5mmϕ

Measured ion flux at Faraday Cup



Ion Energy Distribution

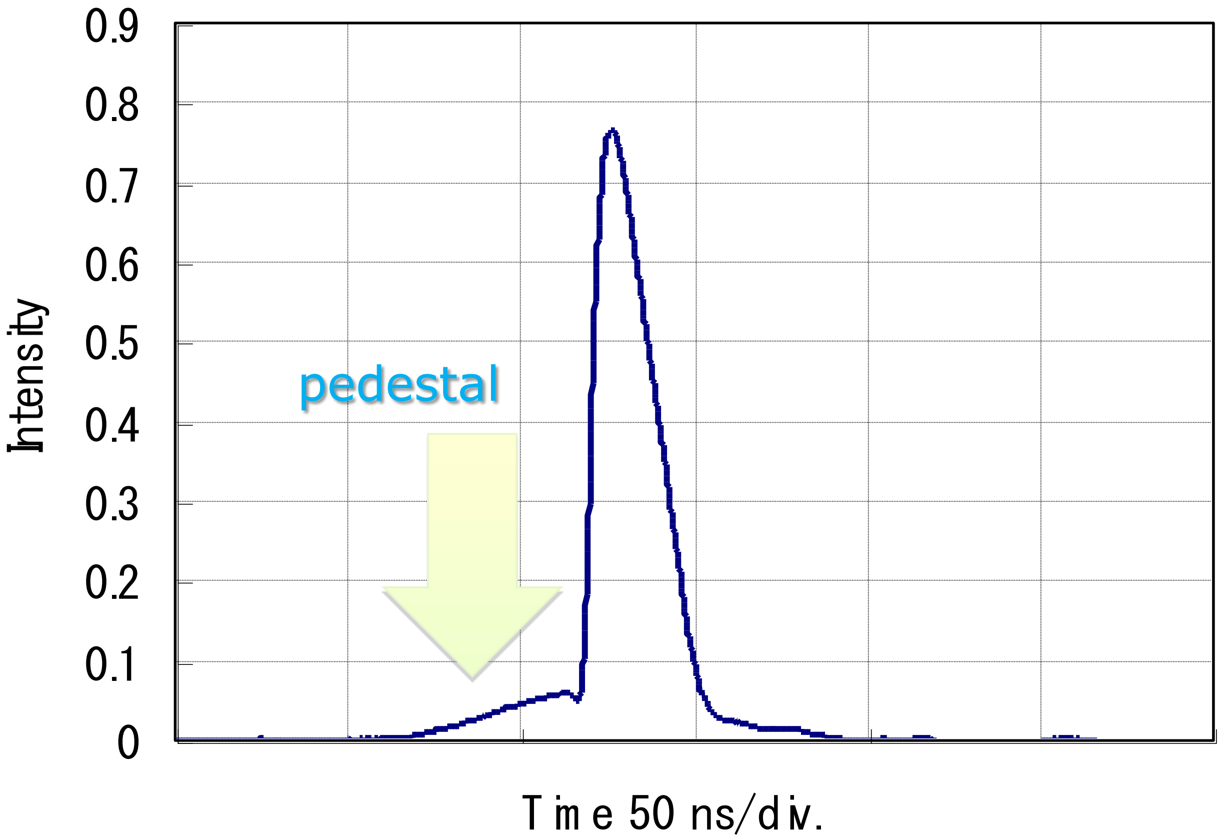


Conclusion on main pulse irradiation

- Full ionization was realized by the combination of Tin mist target and ns CO_2 laser irradiation
- Ion flux was characterized by Faraday Cup measurement
- External magnetic field controls electrons which pulls ions in ambipolar diffusion along magnetic axis

- Total measured charge 2.56×10^{-5} C
- Calculated total charge of $Sn^{+}1$ from 20μm droplet 2.48×10^{-5} C

Laser pedestal : cluster pre-heating



CO_2 laser absorption

Cluster > Atomic gas

Giant resonance in optical absorption spectrum

$\omega_{laser} \sim \omega_p$ (metal cluster)

Cluster heating

Dielectric sphere heating

$$\frac{\partial U}{\partial t} = \frac{1}{4\pi} \mathbf{E} \frac{\partial \mathrm{D}}{\partial t}$$

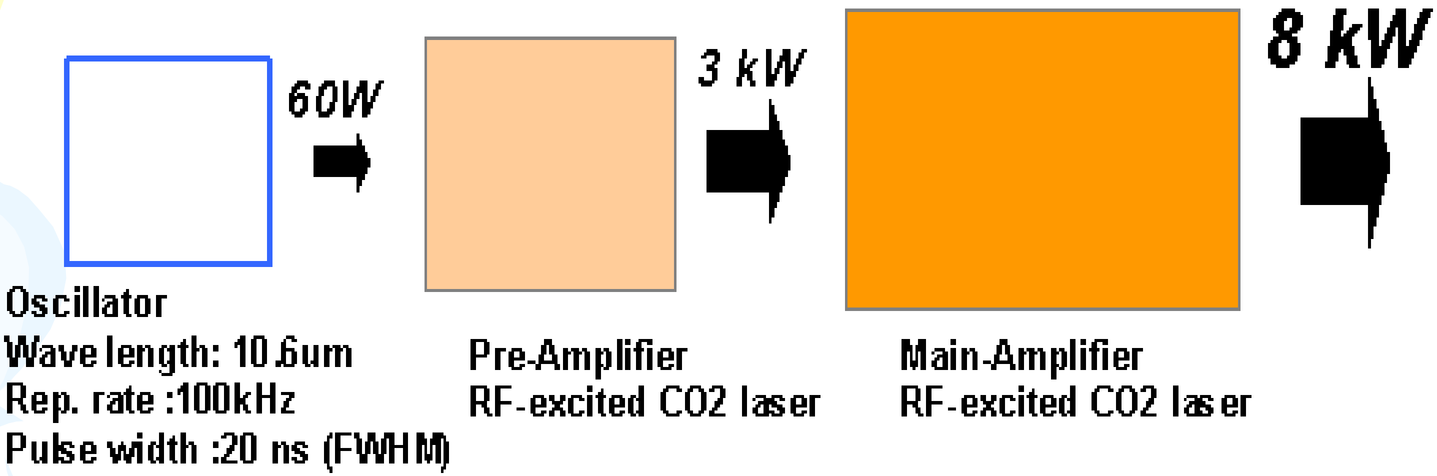
$$\mathbf{D} = \varepsilon \mathbf{E}$$

Pre heating of clusters

- Vaporization – runaway neutral atoms
- Dielectric slow heating of clusters

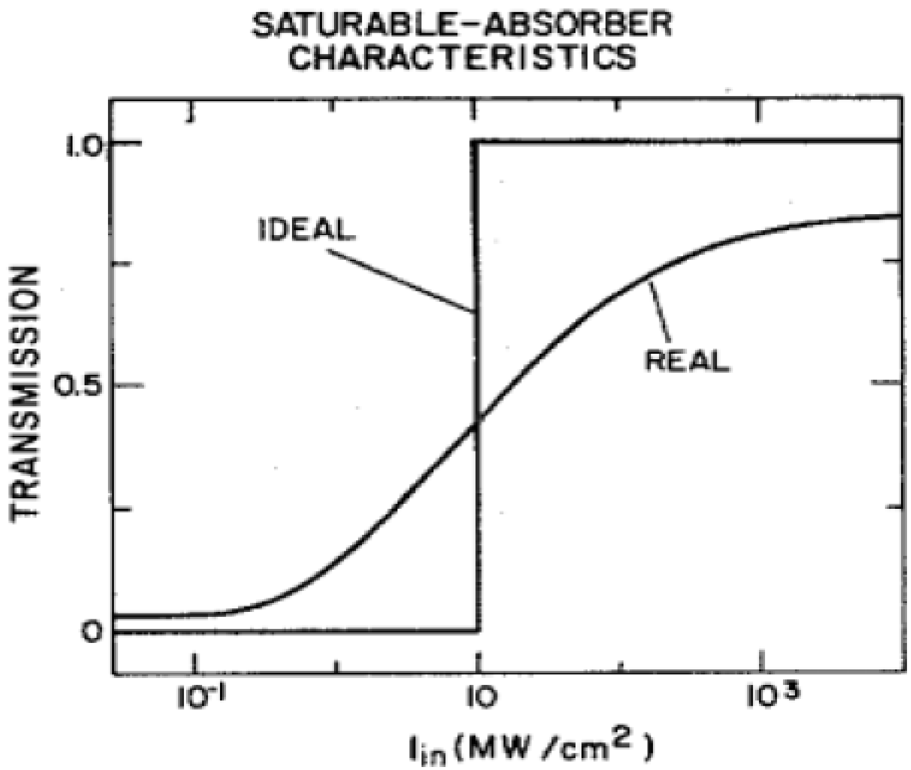
Low pedestal is necessary for low neutral runaway effect from cluster bunch

Typical pulsed CO_2 laser amplifier configuration



Optical isolators are installed between amplifiers

Operational principle of gaseous saturable absorber



General conclusion

Double laser pulse method for clean EUV source

1. Pre-pulse : 5mJ, ps Thin Disc Laser
2. Main-pulse : low pedestal ns CO_2 Laser